Shield to Pin Coupling of Lightning-like Transients on Payload Umbilical Cables on a Launch Pad

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Abstract— **In this paper we describe in-situ testing of a long payload umbilical, on a launch site, injected with "lightning-like" transients and describe resulting pin-to-pin voltages. Injections and voltage measurements near the ground support equipment room, as well as at a location near the payload junction box, are made. The umbilical cables tested include an outer over-braid and the inner conductor coupling is examined for open circuit, short-circuit and various loads representative of spacecraft input impedances. This testing is important because the Kennedy Space Center (KSC) where the lightning occurrence is the highest in the United States, is the primary launch site for Launch Services Program spacecraft customers. Lightning planning is essential but developing a lightning plan is often overlooked or not adequately analyzed leaving the spacecraft vulnerable to time delays or even damage when lightning occurs.**

At other popular launch sites like Vandenberg Air Force Base (VAFB) where lightning occurs less often, although at the same or greater intensity when it does occur, lightning planning is often completely ignored by the spacecraft.

The two major questions to be addressed in the lightning plan are what retesting should be done to establish a "goodness" level and what is the trigger criteria for this testing? The spacecraft will typically use a standard spacecraft check-out procedure to address the necessary retesting, but determining the trigger criteria is often an issue. For instance, a spacecraft needs to understand what their immunity is to a certain lightning magnitude and location. Determining the amount of current that can be coupled onto a spacecraft umbilical can be calculated by using worst case assumptions or measured with current probes and current measurement devices. Spacecraft can also determine what pin-to-pin voltages they are sensitive to, however pin-to-pin voltage measurements are not typically taken during the strike due to the invasive nature of this measurement. In this paper, we present detailed data on the shield to pin voltage transfer functions to provide insight to the spacecraft developers for lightning retest criteria planning.

The results from this unique testing opportunity provide essential details on specific coupling mechanisms affecting spacecraft hardware that interfaces with the ground support equipment. This missing link between cable shield currents and payload susceptibility voltages has been methodically tested and representative data presented.

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1. Introduction

Since most launch vehicles and spacecraft have not been qualified for direct lightning effects, the site is designed to protect from these effects. Most literature, however, focuses on the more serious direct effects and the term indirect is reserved for the progression of a direct strike to an indirect location inside the vehicle. For launch vehicles that have successfully protected from direct effects, the question of impacts to the launch vehicle and payloads for facility strikes and for nearby strikes remains. Typically launch vehicles are designed to withstand these transients and has appropriate retest criteria for the extreme lightning cases. Spacecraft, however, can be much more sensitive. In fact, some spacecraft with RS-422 interfaces in the payload umbilical fear damage from common mode voltages as low as +/- 7 volts.

Testing was performed to establish the relationship between external transients and the differential effects at a launch pad facility. In addition, the relationship between the coupling effects on the payload and ground support equipment side was examined. This is important because there is typically no access to the payload side of the interface to make these direct measurements during the launch campaign. Midway measurements in a junction box are sometimes possible, but still limited accessibility during the launch campaign as well as limited space and resources available (such as power and data for the measurement). Measurement in the ground support equipment room is quite accessible but the relation between these measurements and those actually produced at the payload by the nearby or facility strike is unknown. This work will provide insight into the impact of measurement location.

Direct Strikes to the launch support facility have the primary transfer mechanism from the facility to the payload umbilical via connections on the payload umbilical at multiple points along the facility structure. Based on previously measured data seen on systems such as the Online Lightning Measurement System (OLMS)[1] on a payload umbilical for these facility strikes, it has been observed that the current measured on the payload facility has a significantly lower frequency content than currents coupled from nearby strikes. Simulating the significant current through structure required to drive this facility coupled effect was limited by the test set-up and is beyond the scope of this paper.

The more common dilemma is the resulting coupled currents and voltages from a nearby lightning strike. This effect is not commonly examined in literature because it is insignificant compared to direct and indirect lightning. This paper shows actual measured data from transients coupled onto a payload umbilical shield and measured at various points and loads along the cable bundle (GSE location, umbilical junction connections, and at the payload interface). The test set-up is covered in section 2 of this paper. Section 3 describes the test results. Section 4 provides guidance for the spacecraft and Section 5 is a summary.

2. TEST CONFIGURATION

Set-up

Tests were made at a launch pad on two separate occasions. The general configuration for the measurements made is shown in Figure 1. A load box was used to change the pin-to-pin resistance at either end of the payload bundle for differential mode coupling from injection onto the overall bundle at either end of the umbilical. For the payload end of the umbilical, injection was made onto the over-braid so that the overall shielding and transfer function of the umbilical cable could be evaluated. For the second test period, injection was at the GSE room rack. The overall braid on the umbilical ends before this rack, accordingly this injection site was used to examine a bundle without an overall shield by injecting directly onto a bundle of twisted shielded pairs (TSP). Measurements were made in all cases via a current probe around the wire to the load box across the differential lines. Measurement were made at the injection and load end. A designated TSP wire was terminated with resistive loads. Response was recorded by O-scopes capturing current and voltage waveforms. Measurements at the umbilical junction box were also examined.

An industry standard, lightning test waveform is shown in Figure 2 [2]. Using a Solar Transient Generator and current injection probe, a representative lightning induced current transient was transferred onto the umbilical. One limitation of this test is the point injection was at the point of the injection probe instead of a large scale coupling due to a lightning strike. Hence measurement of the coupled effects at both ends of the umbilical is characterized.

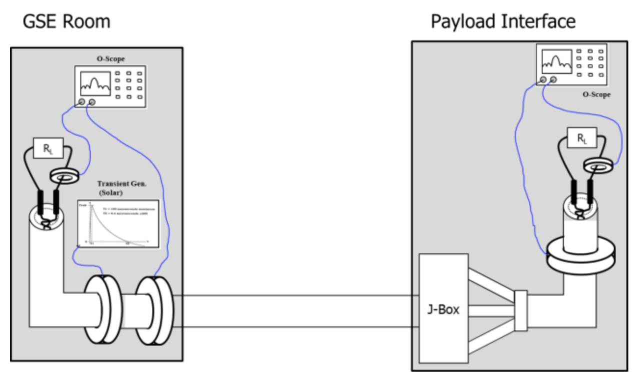

Figure 1. Test Configuration

The injection waveform characteristics are given below:

- Frequency of injected signal: 156 kHz
- Pulse duration: 6.4 us (double exponential)
- Peak level: 500 - 1000 V

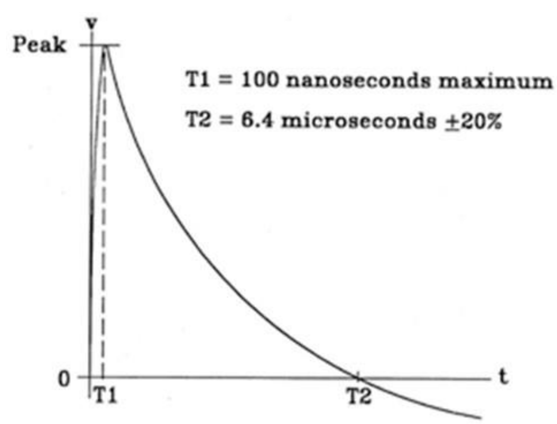

Figure 2. Injected Signal

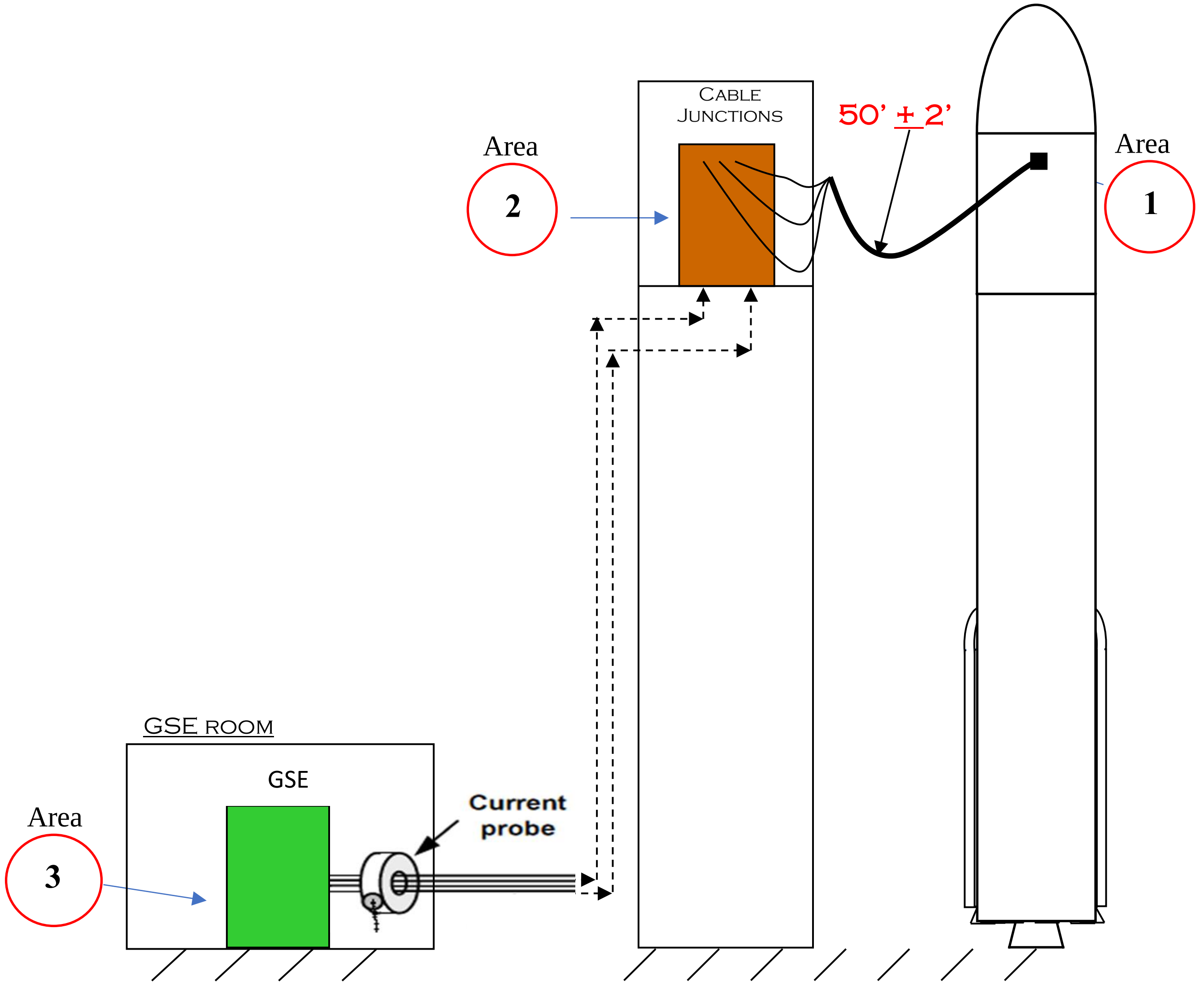

Figure 3. Launch Pad Configuration (GSE injection site shown)

Facility Configuration

The launch pad facility is conceptually shown in Figure 3.

This figure shows the scale of the umbilical with respect to the payload location (P/L)at the top of the launch vehicle (area 1). The facility support structure where the umbilical is draped and where the test measurements were constructed between area 1 and area 2 is not shown. Current probe measurement/injection in the GSE room is shown in area 3.

3. Test Results

Load Configuration and Peak to Peak Measurements

The data in Table 1 shows the resulting pin-to-pin voltages on a single, twisted shielded pair (TSP) in an umbilical with a shielded over-braid. The injections (1000V) were made on the over-braid at the tower at the payload interface portion of the umbilical (see area 1 on Figure 3). Measurements were made there and at the GSE location (area 3 on Figure 1). Current probe factors were ~1 at the frequencies of interest. A more detailed assessment and conversions with the frequency response of the probes is future work, but a coarse examination is made here with the 1:1 conversion factor for comparison purposes.

Area

Table 1. P/L injection and GSE Measurement – 1000V

Load Value		P/L Peak-Peak Current Probe	GSE Peak-Peak Current Probe	~V load (V) GSE
GSE	P/L			
Short	Short	0.842	0.25	
Open	Short	0.725	0.3	
Open	Open	0.19	60	60
1 Ohm	1 Ohm	1.56	0.1	0.1
50 Ohm	50 Ohm	1.43	0.035	1.75
1K Ohm	1k Ohm	1.5	0.03	30
1 Ohm	50 Ohm	1.54	0.18	
50 Ohm	1 Ohm	1.66	0.04	
10 Ohm	10 Ohm	1.5	0.1	
1M Ohm	50 Ohm	1.68	0.8	
1K Ohm	50 Ohm	1.59	0.022	
1 Ohm	Short	0.644	0.05	
Short	1 Ohm	1.63	0.25	

Table 2 shows the current probe measurement and opposite end load voltages at the P/L location for direct coupling onto the bundle of TSP cables. The over-braid was not present on at the rack location where the injection was made. These injections were made with at the 500 Volt level due to improvements in the oscilloscope used in the second test period.

Table 2. GSE injection and PL Measurement – 500V

Load Value		P-P Current Probe		V load (V) P/L
GSE	P/L	GSE	P/L	
Open	Open	0.6	0.01	
Short	Short	0.55	0.04	
Open	Short	0.55	0.03	
Open	1 MOhm	0.59	0.002	
10 kOhm	10 kOhm	0.3	0.0035	35
1 kOhm	1 kOhm	0.35	0.0045	4.5
100 Ohm	100 Ohm	0.28	0.01	1
1 Ohm	1 Ohm	0.23	0.035	0.035

Table 3 shows the current probe measurement and opposite end load voltages at the umbilical junction location (location 2 on Figure 3) for direct coupling onto the bundle of TSP cables in the EEB.

Table 3. GSE injection and Junction Meas. – 500V

Load Value		P-P Current Probe		V load (V) junct
GSE	Junct	GSE	Junct	
10 kOhm	10 kOhm	0.38	0.016	160
1 kOhm	1 kOhm	0.37	0.015	15
100 Ohm	100 Ohm	0.36	0.15	15
1 Ohm	1 Ohm	0.28	0.038	0.038
Short	Short	0.18	0.04	
Open	Short	0.28	0.025	
Short	Open	0.18	0.017	
Open	Open	0.29	0.014	

Waveforms at umbilical loads

The data in Figure 4 shows current probe measurements at the payload location and at the GSE room location (injection site). The time scale is microseconds. There is a significant slowing of the pulse between the injection and measurement locations especially for the lower resistance loads due to inductive time constant effects as demonstrated here for the 1 ohm (GSE) – 1 ohm (P/L) case. Figure 5 shows the same set up for the 1 kohm load case where the signal is faster than the 1 ohm case.

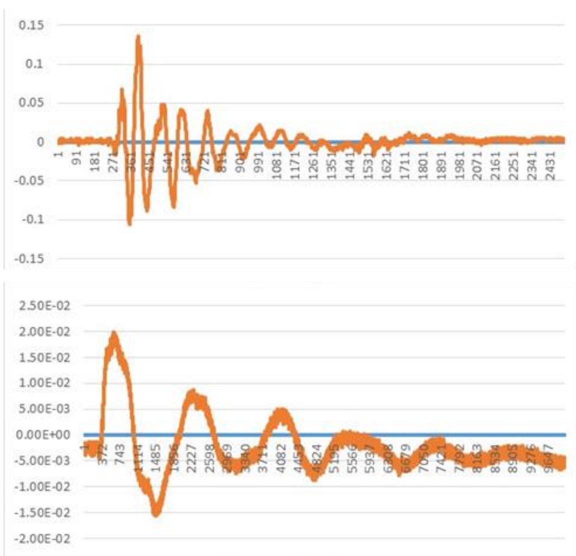

Figure 4. Measured Current Probe Data – Top GSE, bottom P/L – 1 Ohm

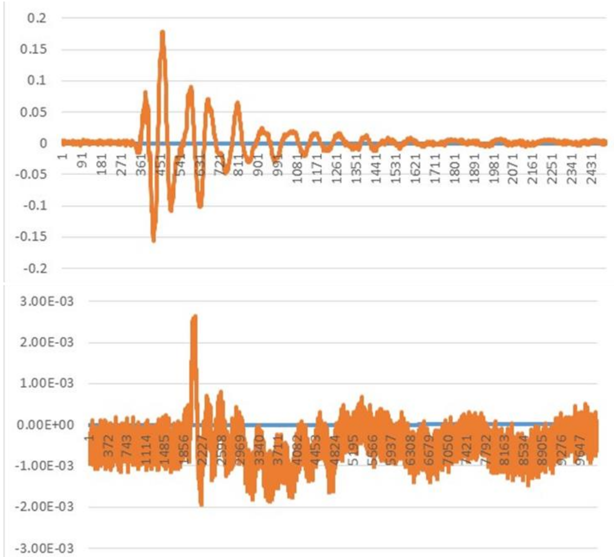

Figure 5. Measured Current Probe Data – Top GSE, bottom P/L – 1 kOhm

Comparisons

Although a full data analysis is future work, a brief comparison is provided here. Examining the voltages across the load on the opposite end of the injection the worst case open circuit voltage for injection onto the overall braid was 60 volts. The typical spacecraft loads showed voltages of less than 2 Volts. The injection voltage used was 1000 Volts and the injection current acts as a 50 ohm load leading to an approximate current of 20 amps (ignoring other contributions from the umbilical impedance and source impedance of the generator). The total umbilical length was approximately 75 meters. Using even worst case transfer impedance, this current would only drive a common voltage of 15 volts. Further comparisons can be made using those voltages predicted by computational models of similar launch sites [3], however this preliminary data of 60 Volts coupled is higher than would have been predicted by standard methods.

There is not a consistent benefit seen between the over-braid case shown in Table 1 and the no over-braid injection shown in Table 2. However, this could be due to the branching of the cables instead of a true single shielded to double shielded comparison.

In all cases (Tables 1, 2 and 3), the value of the load had considerable effect on the voltage difference at the far end of the injection. On the injection end, the load change had only minimal effect. Significant differences are seen along the measurement locations in the umbilical for this test. Consequently, this data shows measurement at a location remote from the payload interface is not a reasonable reflection of the signals expected at the payload interface.

4. SPACECRAFT RESPONSIBILITY

Early spacecraft lightning response planning is essential to have confidence in the health of the spacecraft after a strike and to prevent unnecessary delays. The following is a discussion of a few steps that are key to effective planning.

Voltage Sensitivity

Pin voltage sensitivity is completely a spacecraft function. Typically, there will be some help provided by the launch vehicle or integration team to predict the coupling of a nearby or facility strike to the payload umbilical and the resulting effects as translated to pin-stess voltage. The spacecraft responsibility is to understand its common mode and differential mode sensitivities. A good start is to determine if there are any unprotected RS-422 circuits. Ultimately, this voltage damage sensitivity will be used to create threshold trigger criteria. Data available at ranges is in the form of current amplitude and distance from strike. When a strike occurs, and data is reported, the spacecraft is required to know how much current amplitude at a distance will drive a retest. Further guidance is provided for developing the criteria in reference [4].

It is normally true that the circuits directly interfacing with the payload ground umbilical are the most vulnerable. This is due primarily to the length of the umbilical compared to typical cable runs within the spacecraft. The difference can be orders of magnitude. Cables within the fairing are also protected from the high frequency coupled fields because the fairing slows the rise time of the transient response and thus lowers the coupling efficiency [5].

Design

The Launch service providers have gone a long way to protect from the physical effects of direct lightning attachment to the Upper stage / Payload Fairing employing Lightning Catenary structures to redirect lightning away from the launching vehicle. However, lightning indirect effects still provides significant, potentially catastrophic hazards to both Launch vehicle and Payload avionic sub-systems. Some protections are inherently accomplished through the shielding of electrical components, wiring interconnects, interface connectors, bonding and grounding, but the adequacy of this protection is determined by the spacecraft sensitivity.

The magnitude and proximity of the lightning strike determines the severity of the lightning induced effects, and a good understanding of the transfer function will determine the transient stress at the payload umbilical interface.

Electrical Circuit protection devices can be used to limit the amount energy coupled into Payload / Launch Vehicle sub-systems. The payload umbilical interface is the ideal location for optimal protection but to design adequate protection requires a good understanding of the lightning induced environment and probable stress. This paper is trying to help with that. The launch vehicle provider can also provide protection for the payload, but not always in the ideal location and not always with an intricate understanding of the spacecraft interface design. This can be a factor during ground testing, when the provided protection does not consider the interface circuit topologies, impedances and connections to ground.

Retest Plan

Once the threshold has been exceeded by the reported lightning data, the spacecraft should begin a retest sequence to determine if the spacecraft is healthy and the launch campaign can continue. The minimum set of retest that will allow launch at the next available launch date is ideal. Often lightning occurs in the evening and because of launch commit criteria preventing launch during certain weather conditions there will not be launch attempts during a lightning event. Practically, except for very long launch windows, a lightning storm will automatically postpone the launch to the next available launch window. This gives the spacecraft usually several hours to perform a retest sequence. Another common scenario is lightning occur the evening before a morning launch. In this case, time could be more critical to meet the planned launch opportunity.

It is important to have the retest sequence clearly identified prior to arrival at the launch facility. Some of the important questions include:

- What checks can be made without breaking configuration?
- Is there a worst case (most sensitive) circuit that can be assessed through the payload umbilical connections to GSE?
- Do I need to put the spacecraft into a different configuration for the lightning retest than it will otherwise be in while interfaced with the launch vehicle? For instance, is it necessary to turn on receivers of transmitters, or instruments that have not been planned to be on during the launch portion of the integration? For this case, it is important to coordinate approval for the test cases in an alternate configuration.
- Are there abbreviated test sequences that can be used for a quick assessment?

Some spacecraft rely on launch vehicle criteria alone. That is, if the launch vehicle's retest criteria is met, the spacecraft will retest. One thing to remember with this approach is that the launch vehicle is typically quite robust, likely has diode protection circuitry built into their circuits and has performed extensive transient susceptibility testing, per DO-160 [2] or other rigorous standard. Hence relying on the launch vehicle criteria may not be a conservative approach.

The other extreme used by some spacecraft, is that a too conservative approach is used and a complete functional test of the spacecraft is required. This could require a break in configuration, de-stacking the payload, and significant delays in the mission with associated costs. Finding the balance of confidence in the health of the system within the timeline available is critical.

5. SUMMARY

Measurements have been made on an in-situ launch pad to examine to examine the pin stress from bundle injected voltages. The test configuration was described, data presented and some correlations made. This data review is a work in progress, as such more detailed results are expected at the presentation time. However, this is a step toward creating the translation factors from umbilical currents/voltages to pin stress. Certainly measurement of the precise currents on the umbilical provides better data than predictions from distance.

Furthermore, the spacecraft actions needed to be ready for lightning at the launch site were provided.

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BIOGRAPHY

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